Smallness of Baryon Asymmetry from Split Supersymmetry

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The smallness of the baryon asymmetry in our universe is one of the greatest mysteries and may originate from some profound physics beyond the standard model. We investigate the Affleck-Dine baryogenesis in split supersymmetry, and find that the smallness of the baryon asymmetry is directly related to the hierarchy between the supersymmetry breaking squark/slepton masses and the weak scale. Put simply, the baryon asymmetry is small because of the split mass spectrum.

Introduction.— The hierarchies in the energy scales pose naturalness issues. Cosmological constant is found to be of order $(\text{meV})^4$ [1], while the fundamental scale should be the Planck scale (or the weak scale). To keep the higgs mass around $O(100)$ GeV, a new physics such as supersymmetry must appear at $O(1)$ TeV, although precision electroweak measurements have pushed up this scale higher than $O(5-7)$ TeV, threatening supersymmetry as a solution to naturalness problem associated with the hierarchy problem [2].

These naturalness issues may not be a problem any more in the context of the anthropic landscape of string theory [3]: we may live in such a vacuum that has a very small cosmological constant *and* a very small higgs mass compared with fundamental scale. The fine tuning of the latter led to split supersymmetry (SUSY) framework [4], where the SUSY breaking scale in the visible sector is liberated from the weak scale.

The idea of split SUSY [4] is to abandon solving the hierarchy problem in the standard model (SM) and allow all the scalars except for a higgs to get a heavy mass. Then we can avoid many problems in supersymmetric SM (SSM), such as the absence of a light higgs and most of the sparticles, too fast decay of the proton by the dimension five operators, SUSY flavor and CP problems, and the cosmological gravitino and moduli problems.

The scale of the SUSY breaking is arbitrary in general in split SUSY. The two guiding principles usually taken are the gauge coupling unification at the grand unified theory scale and the lightest SUSY particle as dark matter. In order to satisfy both requirements, gauginos should be kept as light as TeV scale. The simplest mass spectrum is such that all the squarks and sleptons are at $\tilde{m}$ presumably much higher than the weak scale, while keeping all the gauginos and higgs very light. In this case, the gaugino masses $m_{1/2}$ should be suppressed by some mechanism [5], which also keeps A-term small: $A \sim m_{1/2} \sim$ TeV.

How to create the baryon asymmetry of the universe is one of the biggest issues in the modern cosmology. Through the observations of light nuclei [6] and cosmic microwave background anisotropies [7], its abundance is known to be very small: the baryon-to-entropy ratio should be around 10^{-10}. In this Letter, we show that the split SUSY beautifully explains the smallness of the baryon asymmetry of the universe.

In the split SUSY scheme, many aspects of baryogenesis are significantly altered compared to usual supersymmetric SM. For instance, the electroweak baryogenesis [8] does not work both because the strongly first order phase transition cannot be attained due to large stop mass and because available CP violation is also very limited for split mass spectrum. Therefore, other baryogenesis mechanisms should account for the baryon asymmetry of the universe. Here we concentrate on the Affleck-Dine (AD) baryogenesis [9].

The AD mechanism utilizes the squark/slepton condensate to generate the baryon asymmetry. Since the squark/slepton masses $\tilde{m}$ are much larger than the weak scale in split SUSY, the resultant asymmetry is suppressed compared to that in the SSM. As we will see below, in the simplest case, the baryon-to-entropy ratio is given by the ratio between the two split mass scales, the weak scale and the heavy scalar masses $\tilde{m}$: $n_B/s \sim 0.1A/\tilde{m}$, which predicts $\tilde{m} \sim O(10^{12})$ GeV for $n_B/s \sim 10^{-10}$ and $A \sim$ TeV. Thus the smallness of the present baryon asymmetry can be ascribed to the split mass spectrum.

Affleck-Dine mechanism and split SUSY.— In the minimal supersymmetric standard model (MSSM), flat directions including squarks and/or sleptons have baryon and/or lepton numbers, so it can be considered as the AD field, Φ. They acquire heavy SUSY breaking masses of order $\tilde{m}$. In addition, let us assume that the AD field is lifted by a non-renormalizable operator, $W = \Phi^n/nM^{n-3}$, where M is a cut-off scale. In order to produce baryon asymmetry, the AD field must have a torque, whose force comes from the baryon-number-violating A-term. As mentioned above, the same mechanism for obtaining the light gaugino masses makes A as small as $m_{1/2}$. The relevant scalar potential for Φ is

$$V(\Phi) = \tilde{m}^2|\Phi|^2 + \left(\frac{A\Phi^n}{nM^{n-3}} + \text{h.c.}\right) + \frac{|\Phi|^{2n-2}}{M^{2n-6}}. \quad (1)$$

During inflation supergravity and Kähler couplings with the inflaton lead to a Hubble-induced mass term,

$$\delta V = cH_I^2|\Phi|^2, \quad (2)$$

where c is a coefficient of order unity and H_I is the Hubble parameter during inflation. If $cH_I^2 + \tilde{m}^2 < 0$, this negative mass makes the origin unstable and sets the initial value for Φ away from the origin:

$$|\Phi_{\rm inf}| \simeq \min\left[\left(H_I M^{n-3}\right)^{\frac{1}{n-2}}, M_p\right], \qquad (3)$$

where $M_p = 2.4 \times 10^{18}$ GeV is the reduced Planck mass, and this upper bound reflects the fact that the scalar potential becomes exponentially steep above $|\Phi| \sim M_p$. It is worthy of note that H_I should be larger than $\tilde{m}$ in order to develop the large initial amplitude of Φ. In the usual case of low-scale soft SUSY breaking mass, $\tilde{m} \sim$ TeV, this condition is satisfied for most inflation models. However, if $\tilde{m}$ is much larger than the TeV scale as in the split SUSY scheme, this condition sets a nontrivial and severe constraint on the energy scale for the inflation. We will come back to this issue below.

After inflation the Hubble parameter starts to decrease. The AD field tracks the instantaneous minimum given by Eq. (3) with H_I replaced by H, the Hubble parameter at that time. When $H \sim \tilde{m}$, the AD field comes to oscillate, and the baryon number density is efficiently produced at the same time:

$$n_B \simeq B_\Phi \delta\, A |\Phi_{\rm osc}|^2, \qquad (4)$$

where B_Φ is the baryon charge of Φ, $\delta \sim O(0.1)$ represents a CP phase, and $|\Phi_{\rm osc}| \equiv (\tilde{m} M^{n-3})^{1/(n-2)}$ is assumed to be smaller than M_p. The resultant baryon-to-entropy ratio depends on the subsequent thermal history. For simplicity, let us first consider the case that the AD field dominates the energy density of the universe when it decays. Then the baryon-to-entropy ratio is

$$\frac{n_B}{s} \simeq \frac{n_B}{\rho_{tot}/T_d} \sim \frac{B_\Phi \delta\, A T_d}{\tilde{m}^2} \sim 0.1 \frac{m_{1/2}}{\tilde{m}}, \qquad (5)$$

where $T_d \sim \tilde{m}$ is the decay temperature of the AD field, which decays into the gauginos and quarks/leptons. Note that the decay does not proceed until the effective masses of decay particles become smaller than the parent mass, $\tilde{m}$, resulting in $T_d \sim \tilde{m}$.

From Eq. (5) we can see that the baryon asymmetry is suppressed by the hierarchy between the gaugino mass and the squark/slepton mass. Because of the large hierarchy in split SUSY, a desired value of $n_B/s \sim 10^{-10}$ can be obtained if $\tilde{m}$ is around 10^{12} GeV for $m_{1/2} = 1$ TeV. This is rather amazing result; the observed small baryon asymmetry is simply determined by the split mass spectrum in the SSM, independent of n or M as long as the AD field dominates the universe. This should be contrasted to the usual case of $\tilde{m} \sim$ TeV leading to $n_B/s \sim O(0.1)$.

The conditions for the AD field to dominate the universe are easily achieved. If the reheating is completed before the AD field starts oscillating, i.e., $T_{RH} > \sqrt{\tilde{m} M_p}$,

$$|\Phi_{\rm osc}| > \left(\tilde{m} M_p^3\right)^{\frac{1}{4}} \qquad (6)$$

must be satisfied, where T_{RH} is the reheating temperature after inflation. On the other hand, for $\sqrt{\tilde{m} M_p} > T_{RH} > \tilde{m}$, we obtain a similar inequality,

$$|\Phi_{\rm osc}| > \sqrt{\frac{\tilde{m}}{T_{RH}}} M_p. \qquad (7)$$

It is easy to see that (6) is satisfied for e.g., $n = 6$ and $M \gtrsim M_p$.

It should be emphasized that cosmological gravitino problem [10] can be avoided, since the gravitino mass $m_{3/2}$ can be much larger than the TeV scale in split SUSY. Thus, the reheating temperature can be as large as 10^{16} GeV. However it is still nontrivial whether the gravitinos dominate the universe and produce extra entropy at the decay, destroying a simple relation Eq. (5). Let us therefore clarify the condition for gravitinos not to dominate the universe. For $m_{3/2} \gtrsim \tilde{m}$, the gravitinos are mainly produced through scattering processes, although one can easily see the gravitinos produced in this way give only negligible contribution to the energy density of the universe. On the other hand, for $\tilde{m} > m_{3/2}$, potentially dangerous process is the decay of the squarks/sleptons into gravitinos, and the abundance of the gravitinos is solely determined by this process [5]:

$$Y_{3/2} \sim 10^{-5} N \left(\frac{\tilde{m}}{10^{12}\mathrm{GeV}}\right)^3 \left(\frac{m_{3/2}}{10^9\mathrm{GeV}}\right)^{-2} \left(\frac{g_*(\tilde{m})}{10^2}\right)^{-3/2}, \qquad (8)$$

where $g_*(\tilde{m})$ counts the relativistic degrees of freedom at $T = \tilde{m}$, and N is the number of thermally populated squarks/sleptons at that time. Note that since the decay temperature of the AD field is of the order of $\tilde{m}$, not all the squarks and sleptons might be thermally populated. Also, even if none of them are thermally produced, there is still contribution from the decay of the AD field (squark/slepton condensate) into gravitinos. Thus N varies from a few to a few tens, depending on the detailed structure of the sfermion mass spectrum and composition of the flat direction. In order to keep the direct relation between the baryon asymmetry of the universe and the mass hierarchy in split SUSY, the gravitino should not dominate the energy density of the universe when it decays. Thus, we obtain the constraint on the gravitino mass as

$$m_{3/2} \gtrsim 10^9 N \left(\frac{g_*(\tilde{m})}{10^2}\right)^{-3/5} \left(\frac{g_*(T_{3/2})}{10^2}\right)^{1/10} \times \left(\frac{\tilde{m}}{10^{12}\mathrm{GeV}}\right)^{6/5} \mathrm{GeV}. \qquad (9)$$

where $T_{3/2}$ is the decay temperature of the gravitinos:

$$T_{3/2} = 4 \times 10^3 \left(\frac{g_*(T_{3/2})}{10^2}\right)^{-1/4} \left(\frac{m_{3/2}}{10^9\mathrm{GeV}}\right)^{3/2} \mathrm{GeV}. \qquad (10)$$

When the gravitino mass is smaller than 10^9 GeV, there is an extra entropy production, which dilutes the baryon asymmetry. The dilution factor is estimated as $\sim (m_{3/2}/10^9\ \mathrm{GeV})^{-5/2}$.

In the above discussion, we have assumed that the Q balls [11] are not formed. Q balls may delay the decay of the AD field and affect the direct relation between the baryon asymmetry and the mass hierarchy. Here we show that Q balls are actually absent in the context of split SUSY. In order to have the Q-ball configuration, the effective potential of the AD field must be shallower than $|\Phi|^2$. Including one-loop corrections to the squark/slepton masses, the effective potential scales as $|\Phi|^{2+2K}$, where K is the coefficient of the one-loop corrections. Hence the Q-ball solution exists, if and only if K is negative. If squark/slepton masses are comparable to the gaugino masses, i.e., $\tilde{m} \sim m_{1/2}$, the one-loop correction is dominated by negative contribution from the gauginos, therefore Q-ball configuration exists, leading to Q-ball formation. However, if $\tilde{m} \gg m_{1/2}$ as in split SUSY, this is not necessarily the case. In particular, for $\tilde{m}/m_{1/2} \sim 10^9$, K is always positive, irrespective of whether or not the flat direction includes the third-generation fields. Therefore, there is no Q-ball configuration in the split SUSY.

Now let us consider fluctuations inherited in the baryon asymmetry. If the AD field acquires primordial fluctuations during inflation, the baryonic isocurvature fluctuation generally arises. In particular, as extensively studied in the context of curvaton scenario [12], the primordial fluctuations in the AD field cannot account for the present density fluctuations, since the baryonic isocurvature would then become too large [13]. Thus the primordial fluctuations in the AD field must be either subdominant compared to the inflaton-induced adiabatic fluctuations or suppressed by the Hubble-induced mass term and/or A-term.

Next let us study what if the AD field decay before its domination of the universe. In this case, the entropy of the universe almost entirely comes from the inflaton, leading to

$$\frac{n_B}{s} \simeq \frac{B_\Phi \delta\, A|\Phi_{\rm osc}|^2}{\tilde{m}^2 M_p^2} \min\left[T_{RH}, \sqrt{\tilde{m} M_p}\right]. \qquad (11)$$

Although the split mass hierarchy explains the smallness of the baryon asymmetry to some extent, the direct and simple relation like Eq. (5) is lost.

Finally, we would like to mention that in our scenario radiation of the present universe mainly comes from the AD field rather than the inflaton [14]. Since the SM degrees of freedom are naturally created by the decay of the AD field, this feature can be considered as a merit of making easy to build inflation models. One of the other ways to realize the feature is to drive inflation itself within the SSM. For instance, the MSSM flat direction could drive the (chaotic) inflation with the quartic potential [15] or even the quadratic potential with the inflaton mass $m_I \sim \tilde{m} \sim 10^{13}$ GeV in split SUSY.

Conclusion.— We have considered the AD baryogenesis in split SUSY model, in which all the scalars except for a finely-tuned higgs get a heavy mass $\tilde{m}$, while gauginos (and higgsinos) have a weak scale mass. It was found that the small baryon asymmetry of the universe directly results from the mass hierarchy between them. To be specific, as is clear from Eq. (5), the heavy scalar mass scale $\tilde{m}$ should be around 10^{12} GeV, to explain the baryon-to-entropy ratio $n_B/s \sim 10^{-10}$ for $m_{1/2} \sim$ TeV. It is interesting that thus predicted value of $\tilde{m}$ is close to the upper limit $\tilde{m} \lesssim 10^{13}$ GeV, which comes from the requirement that the lifetime of gluinos should not exceed about 10^{16} sec [4].

In addition, this scenario suggests high reheating temperature of the inflaton, which in turn implies high-scale inflation. Thus, the detailed observation of the tensor mode or BB mode of CMB polarization may favor or refute our scenario.

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